Navigation Overview

Strategic and Technical Aspects of Planetary Small Satellite Missions

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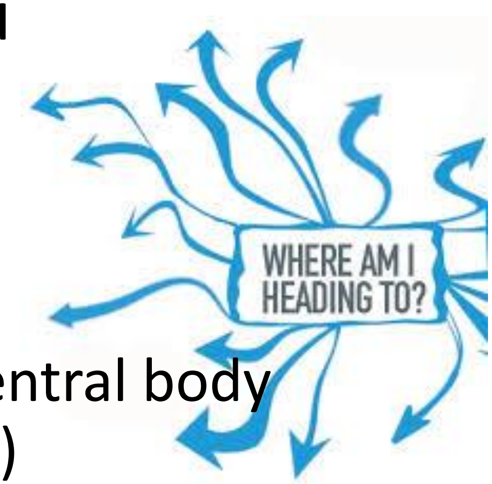
Agenda

- Orbit Regimes
- Basic Navigation Concepts
- Data Systems and Types
- Influences on Measurements
- Planetary Navigation Options
- Future Directions

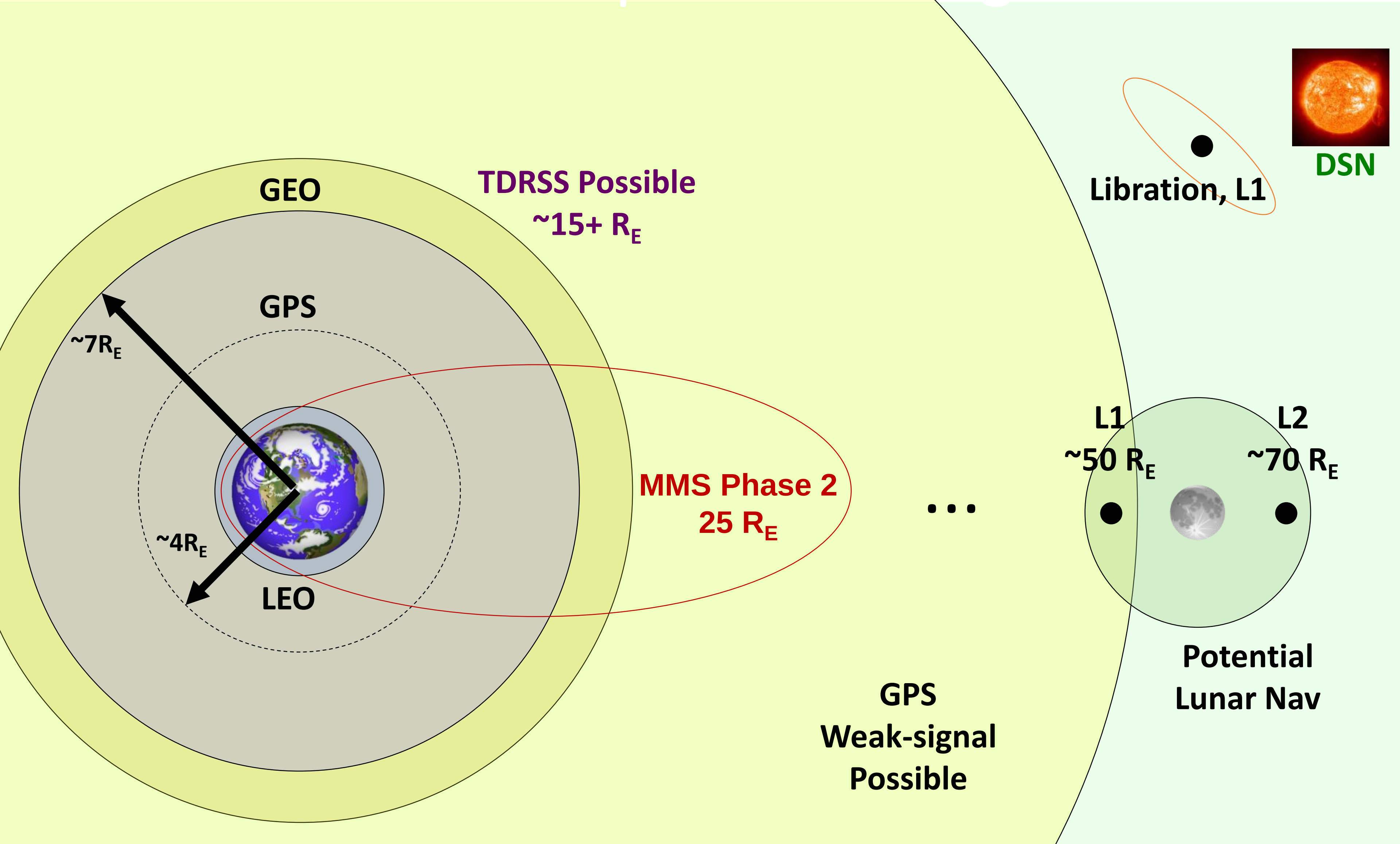
Defining Navigation Regimes

- **Near Earth – central body is Earth or within $2e^6$ km of Earth**
- **Planetary – Moon, Planets and their moons, Asteroid**
- **Heliocentric – Non-Planetary designs, Drift away**



- **Navigation refers to:**
  - Knowledge of the mission orbit wrt the central body (absolute) or wrt another object (relative)
  - Knowledge of where the object resided or currently resides in the orbit (definitive) or will reside in the future (predictive)
  - The trajectory design associated with achieving the mission
  - How to modify the object's orbit to follow that trajectory,
  - And the time associated with each of these

Notional Summary
Near-Earth Operational Regimes



Forms of Direct Measurements

- Time Delay → Range (Distance)
- Differential Delay → Angle
- Frequency shift (Doppler)
  or Carrier Phase → Line of Sight Velocity
- Frequency Change Rate → Line of Sight / Acceleration
- One common element among each of these…

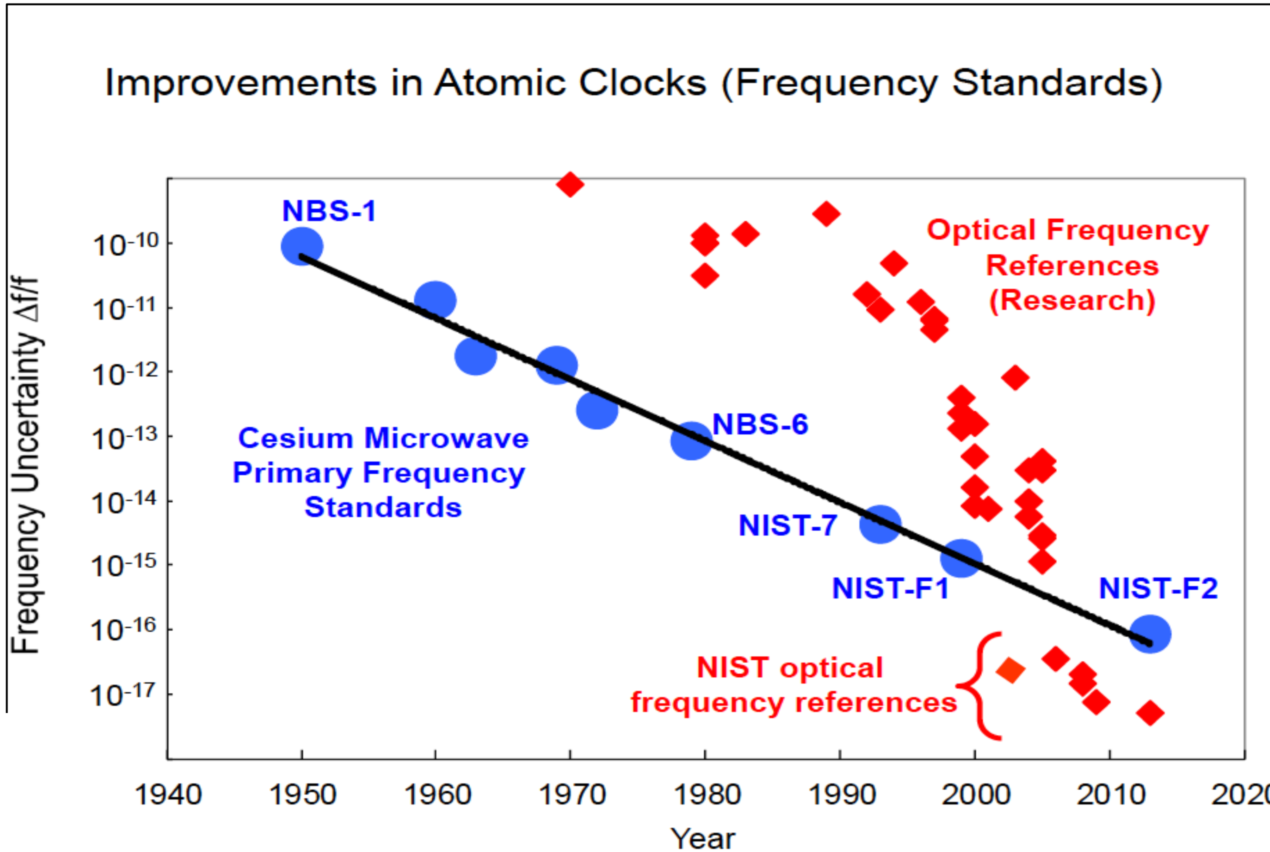
TIME

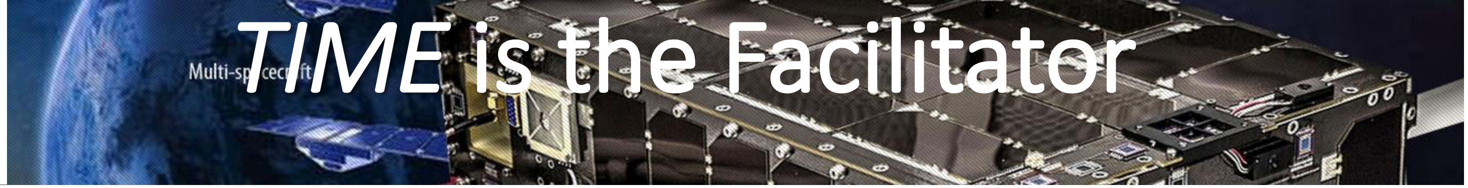
Time is Fundamental


TCXO

OCXO

Cs





TIME is the Facilitator

- Ground element timing establishes boundary condition for end-user performance
- Applicable to communications, radiometrics, and science
- Sources clock and frequency
    - Delay accountability
    - Phase noise & jitter
    - Coherency

- Automatic exchange of timing state during a communication session enables:
    - TDMA type communication schemes - **Time-division multiple access** (**TDMA**) is a channel access method for shared-medium networks. It allows several users to share the same frequency channel by dividing the signal into different time slots
    - Autonomous or on-demand session establishment
    - Internet-like routing

Data Types & Systems

Measurement Type	Providing Systems
Range – tone, swept tone	GN, TDRS TTC, DSN
Range – PN	TDRSS, GPS, DSN (variation)
Doppler or Carrier Phase	All
Angles – Direct Observation	GN, TDRS (WSC SGL, SA & MA beams)
Celestial Navigation – Indirect Angles	Star Sensors, Earth/Sun Sensors
Delta Differenced One-Way Range - Angles	DSN with Quasars
Imaging/Optical Navigation	Cameras
XNAV	X-Ray Pulsars

Range & Doppler can be either 1-way or 2-way
Both improved by differencing

Error Sources on Radiometrics

- Media – phase delay
- Oscillator stability – ground, relay, customer*
  - Local Oscillators and the respective Phase Lock Loop
  - Includes resolution of Numerically Controlled Oscillators (NCO)
- Thermal Noise
- Loop Order – ability to track higher order dynamics
- Signal to Noise Ratio & integration time
- Calibration
- Tone selection – resolution limitations
- Coherency – precision of turnaround
- Platform calibration – location, orientation

* - Does not apply to coherent operations; Can be differenced out with adequate source availability

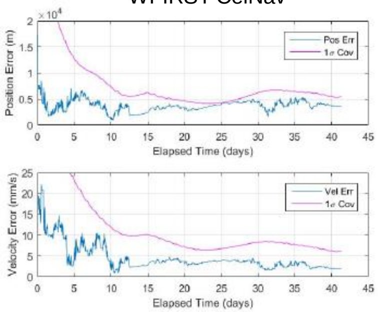
Planetary Navigation

- Planetary Navigation options include traditional ground based and Onboard Celestial Navigation
- Traditional option includes the use of the NEN and DSN and a DSN compatible transponder, e.g. IRIS-V2, and requires multiple station contacts
- Onboard options include the use of Celestial Navigation, a self contained onboard system, developed for libration, cis-lunar, and deep space missions
  - Equipment - quality depends on the mission and orbit regime & requirements
    - **Transponder** with ability to accept external reference and to output low phase noise Doppler (<<1mHz, like 0.3mHz)
    - **Oscillator** with Allan Variance <1e-12 (prefer 1e-13) over tau of 10-100 seconds
    - **Accelerometer**
    - **Star sensor** broad FOV allows for the largest variety of observations with adequate dynamics to meet the solution requirements
    - **Onboard timing synchronous** across all systems related to nav (XPDR, XLINK, C&DH, Nav processor, accelerometer, star sensor observables)
    - **Processor**
    - **Xlink for Formation** –incorporate relative Doppler and pseudo range, referenced to the same oscillator as the XPDR; the ambiguity has to be tunable or allow for the far field distances, but while maintaining near field accuracy.
- Improved accuracy and convergence using onboard system, especially for frequent maneuvers for formation control and any momentum uploads
- Requirements, math specs, & Users' Guide that contain the specs for CelNav are available

Autonomous Celestial Navigation (CelNav)

- **Technology Demonstration Concept**:
  - Autonomous, on-board celestial navigation system fused with one-way radiometrics, accelerometers, Goddard Enhanced On-board Navigation System (GEONS), and Goddard Image Analysis and Navigation Tool (GIANT). Would provide autonomous Gateway navigation.
- **Relevance:**
  - Made up of existing high-TRL components with flight heritage (MMS, OSIRIS-Rex) and flight-proven software. Multi-center collaboration
  - Answers specific need for WFIRST flagship mission, common hardware proposed for Caesar and Lucy

WFIRST CelNav*

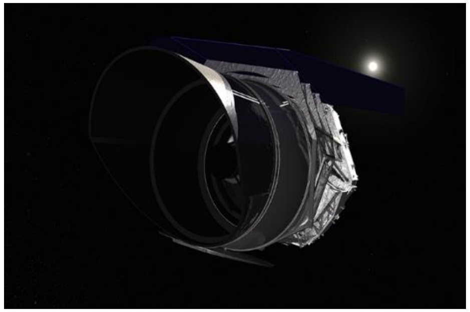


On-board OD (CelNav + 1-way Doppler) for WFIRST
5 – 30 km, **15 - 50 mm/s**, 3-sigma RSS

Ground OD (NEN) based on recent experiences (multiple)
0.2 – 1 km, **200 – 500 mm/s**, 3-sigma RSS

Performance is orbit/mission dependent
Gateway-specific analysis pending

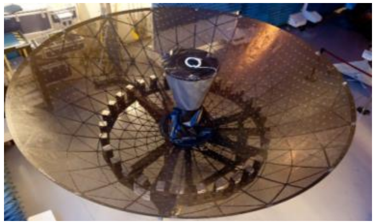
- **Relation to Current Activities:**
  - Testing of an autonomous celestial navigation system would directly support technology maturity for the WFIRST on-board navigation system.
    - Gateway & WFIRST on-board OD is more accurate for maneuver planning than ground based navigation alone and will save fuel, extending mission lifetime
    - Reduces DSN/NEN contact times for ranging
    - Aides relative navigation for potential WFIRST/Starshade mission

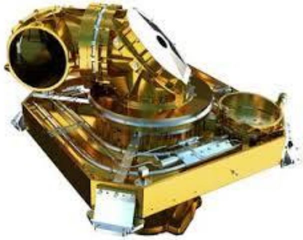


- **Onboard Requirements:**
  - Mass & power allocations,) select celestial body ephemerides, camera FOVs to view select celestial bodies, access to ACS data, access to onboard radiometrics useful

Incorporate Optimetrics

- Radiometrics: A measure of the change in a parameter associated with a radio frequency-based signal that can be used as an observable of direction, range, or relative velocity between two objects.
- As NASA moves toward optical communications, the navigation systems will adapt and can benefit.





- Optimetrics: Same as radiometrics, but using an optical signal as the source to provide orders of magnitude increased accuracy on the observables.
- Range to ~10um and range rate to ~20um/s at 622 MBPS data link rate, achieved through communication data clock phase measurements. Continuous optical carrier phase measurements advanced the Doppler accuracy to 60nm/s.
- Provide immunity from ionosphere and interplanetary plasma noise floor, and plasma scintillation which is a performance limitation for RF tracking. The techniques enable the precision required for gravity-wave and interior composition science, helio-physics, and precision formation flying.

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Goddard Optical (image-based) Navigation

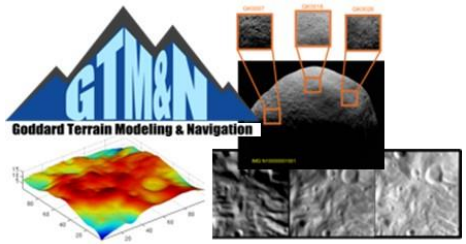
Technology/Capability

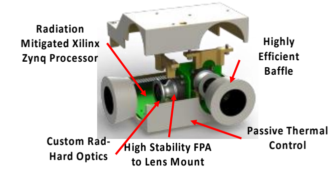
- Optical Navigation (OpNav) refers to a number of methods of extracting relative state information between a spacecraft and targets observed with a digital camera.
- Four components: unresolved center-finding (bearing), resolved center-finding (Multiple bodies), limb-based OpNav (relative info plus range) , and surface feature navigation (SFN) (Bearing to know landmarks).
- All three components can either be performed on the ground or autonomously on-board.
- Currently capable of producing measurements with errors of less than 1 pixel and processing irregularly shaped bodies as exercised on OSIRIS-Rex.

Status/Plans

OpNav is applicable to almost all deep-space and small body missions, and even to non-traditional near-earth missions that seek to decrease cost and reliance on radiometric tracking. A sample of current/potential customers:

- OSIRIS-REx
- CAESAR
- LUCY
- WFIRST
- New Frontiers 5
- Cubesat missions





Relevance/Importance

- Observables required for the precision relative navigation
- Required on many deep space and small body missions.
- OpNav decreases the reliance on ground-based radiometric tracking, decreasing cost and congestion on the space communication networks.

Comparative Assessment

- Goddard currently has access to state-of-the-art OpNav tools which provide access to state-of-the-art OpNav algorithms that *meet or exceed* the capabilities of other centers and companies:
  - Ground-based Goddard Image Analysis and Navigation Tool (GIANT) for unresolved/resolved center-finding, limb-based
  - Ground-based Stereophotoclinometry (SPC) software for TRN and surface modelling
  - Retina onboard TRN tool

- GIANT is currently TRL 7 and will be TRL 9 by the end of FY 2019.
- Current efforts focus on migrating all ground-based OpNav capabilities to autonomous onboard capabilities as a critical part of the autoNGC suite.
- Fully autonomous onboard navigation represents the future of space exploration as ground based navigation becomes unfeasible due to time delays and cost.
- Miniaturizing and/or integrating components enables SmallSats and CubeSats

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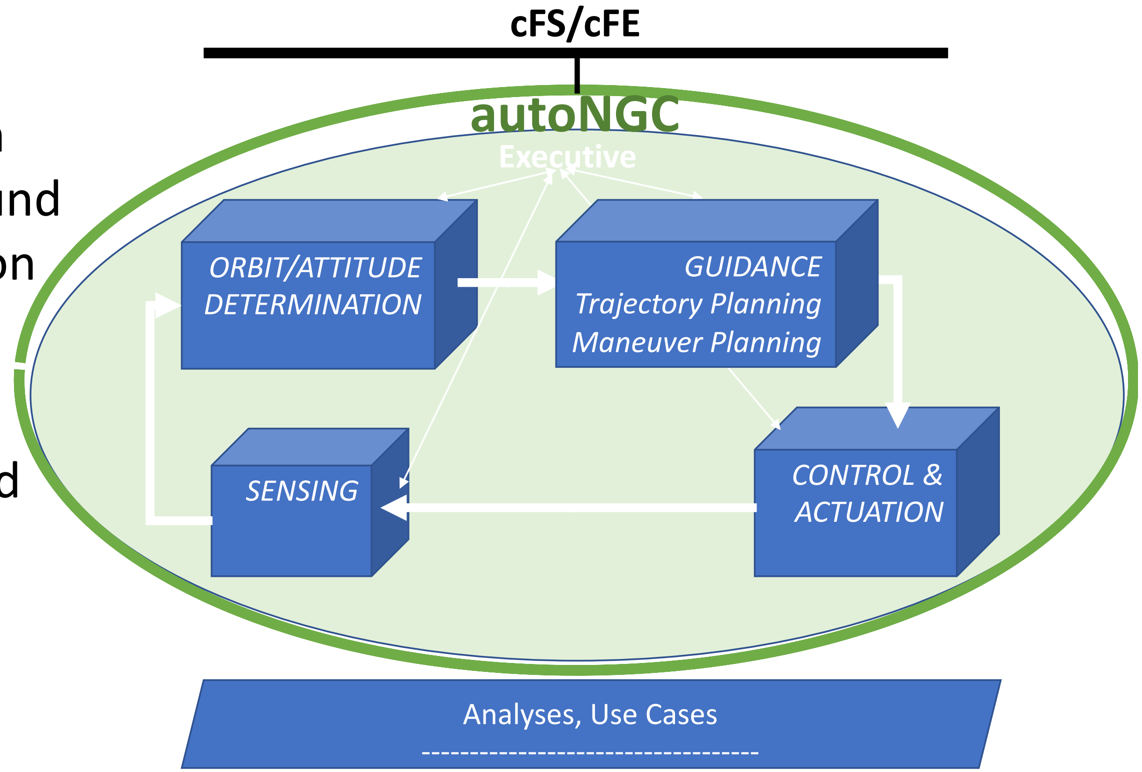
Autonomous Navigation, Guidance, Control

- Follow-on to onboard orbit estimation is onboard orbit control: autonomous maneuver planning, execution, and calibration
- AutoNGC demonstrated on EO-1 in 2000; Established for single mission
- Reduces ground ops required for maneuver planning and execution and associated risks
- Requires telemetry feed from the maneuver, similar to ground planning/execution/calibration process
- Algorithms for formation missions not yet implemented in FSW



Simplified Measurement Capability

- Broad summary of measurement capability
  - Not intended to indicate one size fits all
  - Some measurements not available in real-time
  - Snowflake-like possible combinations for performance & robustness

Orbit	GPS	TDRSS	NEN/DSN	ΔDOR (DSN)	CELNAV/ Optical	Requirement/ Source
LEO	50 cm @ 1 Hz	2–8 m @ 1.5 orbit	10–20 m @ 1.5 orbit	N/A	1 km @ 2 hr	≤ few m
HEO (perigee < constellation)	10 m @ 1 Hz	100 m	100 m	N/A	0.1–15 km @ 1 orbit	< 1 km / many
GEO	5 m @ 1 Hz	N/E	100–200 m @ 36 hrs	N/A	1–5 km @ 1 orbit	0.1 km / many
Lunar, in view	N/A[a]	N/E	200m @ 2 days	1 km @ 1 day	0.5 km @ 0.5 days	0.5 km / LRO
Lunar, far side/hi lat	N/A	N/A	N/A	N/A	0.5 km @ 0.5 days	0.5 km / LRO
Sun-Earth L1/L2	N/A	N/A	4-32 km @ 3 wks	1 km @ 1 day	5–15 km @ 3 days	8 km / WFIRST
Planetary	N/A	N/A	8-15 km @ 3 wks	1 km @ 1 day	5-10 km @ 3 days	~ 5 km / Lucy

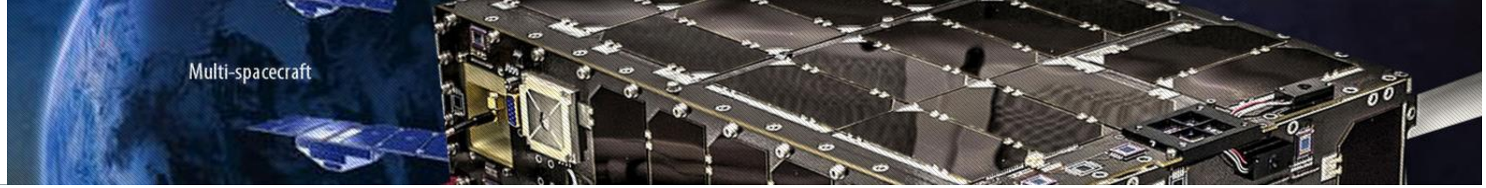
Generalized/Simplified Navigation Categories

- Broad summary of navigation categories
  - Not intended to indicate one size fits all
  - More snowflakes
    - Mission unique elements
    - Combination of many known components

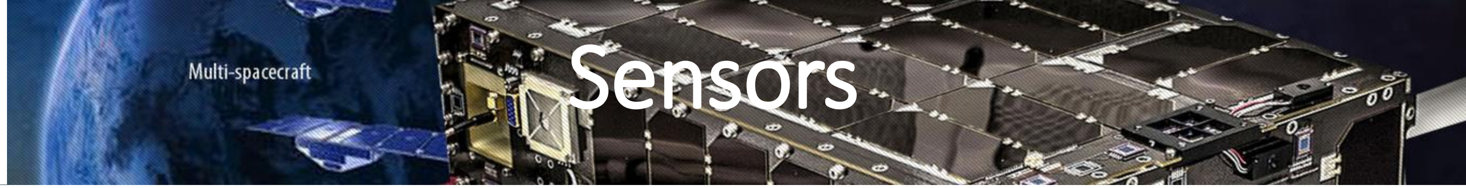
Category	Lower Accuracy	Accurate	High Accuracy	Precision Navigation
Absolute Definitive	100 – 300 m	5 – 40 m	50 cm – 10 m	< 1mm – 50 cm
Absolute Predictive (1 day)	1 km	75 – 500 m	5 – 50 m	5 cm – 5 m
Relative Definitive	1 – 50 m	1 – 10 m	0.1 – 1 m	<0.1 mm – 1 m
Relative Predictive (1 day)	<0.5 km	50 – 75 m	1 – 10 m	0.1 mm – 10 cm
Science Objective	Astro, Spatial, Loose temporal	Temporal, Surface Observer, Human	Temporal, Surface Observer/Altimetry, Human	Altimetry, Gravity, Interior Composition
Orbit Regime	Low, libration, helio cruise, cis-lunar cruise	Low, GEO, High, loose formation, precise maneuvers	Low, GEO, High, approach, formation, cluster	low, GEO, High, precise formation, rendezvous/docking

Planetary Navigation Summary

- Navigation in the near-earth regime, $2e^6$ km, can be performed by a wide array of systems to provide robust solutions with seamless transitions between orbit regimes
- Navigation in the planetary regime has limited options with traditional ground support using radiometric tracking, onboard systems, and relative options available
- Many components within a communications system influence the resultant radio/optimetric tracking data quality
- GSFC Navigation offers relevant pre- and post-launch services to the user and networks communities
- Navigation needs to be an enabler for the science NASA hopes to achieve in the future – technology investments are key



BACKUP



Sensors

- GPS Receiver
  - GSFC developed weak-signal GPS; licensed to companies (BRE)
  - Assists in coverage in higher altitudes
- Global Navigation Satellite System (GNSS)
  - Advancing to additional signals (L2c, L5), including other constellations (Galileo, Glonass, Compass)
- Crosslink
  - Developed as element integrated with weak-signal GPS receiver to TRL 5 for MMS
  - 1-way range measurement for relative navigation
  - Low-rate data on signal (exchange science alerts, H&S, nav)
- Autonomous Rendezvous and Docking Sensor
- XNav sensor; translates pulsar timing to pseudo-range observation
- Star Sensor
- Accelerometer
- Integrate navigation sensor with communications receiver

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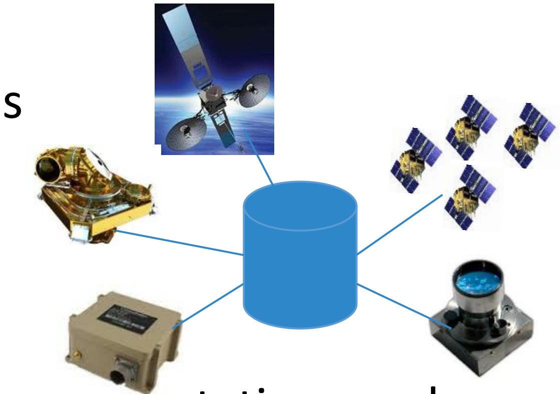
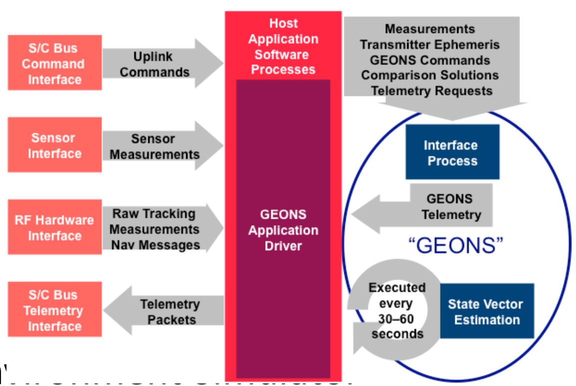
Systems

- Fusion of multiple data types from independent systems
  - Robust to outages or shortcomings of any one system
  - High accuracy
  - Seamless transitions across orbit regimes



- GEONS flight software processes forward Doppler from ground stations and TDRSS, attitude sensor data for celestial nav, GPS, crosslink & NGBS pseudo-range, XNav
  - Solves for absolute and relative navigation
  - Future data types: optimetric, optical imaging
  - Plans to upgrade to C++

Host Applications Use Their Own Driver to Access GEONS Methods



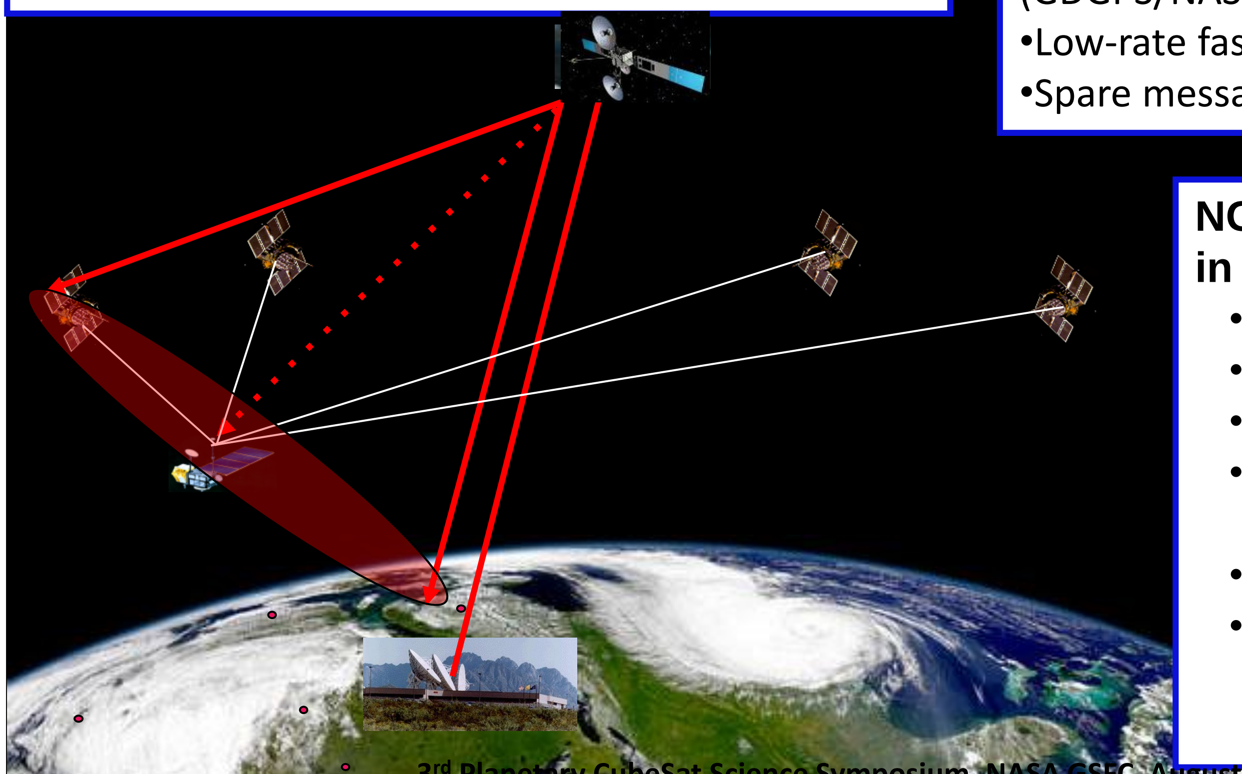
- Test Facility: Formation Flying Test Bed
  - Provides Test As You Fly simulation capability
  - GPS simulator, Path Emulator for RF Signals, User Dynamics En

- From the spacecraft side, as comm subsystem is developed, nav and comm engineers need to work together to define requirements

Next Generation Broadcast Service (NGBS)

NGBS Message Includes:
- TDRS ephemeris and health/status information (FDF, WSC)
- 0.5 Hz GPS corrections (GDGPS)
- 5 sec GPS integrity alarms (GDGPS)
- Data authentication (GDGPS)
- Earth orientation (GDGPS)
- Space environment/weather data (GDGPS/NASA GSFC CCMC)
- Low-rate fast-forward user commands (MOC)
- Spare message bits for future content

NGBS Signal Consists of:
- Low-rate data message (< 1 kbps)
- PN ranging code synchronized with GPS time
- A wide "earth coverage" beam transmitted from three TDRS locations to provide global coverage to >1000 km altitude



NGBS provides direct benefits in the following areas:
- Science/payload missions
- Human Space Flight missions
- SCaN/Network operations
- GPS and TDRSS onboard navigation users
- TDRSS performance
- New capabilities consistent with the modern GNSS architecture